

Are we witnessing the epoch of reionisation at $z = 7.1$ from the spectrum of J1120+0641?

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ABSTRACT

We quantify the presence of Ly α damping wing absorption from a partially-neutral intergalactic medium (IGM) in the spectrum of the $z = 7.08$ QSO, ULASJ1120+0641. Using a Bayesian framework, we simultaneously account for uncertainties in: (i) the intrinsic QSO emission spectrum; and (ii) the distribution of cosmic H I patches during the epoch of reionisation (EoR). For (i) we use a new intrinsic Ly α emission line reconstruction method (Greig et al.), sampling a covariance matrix of emission line properties built from a large database of moderate- z QSOs. For (ii), we use the Evolution of 21-cm Structure (EOS; Mesinger et al.) simulations, which span a range of physically-motivated EoR models. We find strong evidence for the presence of damping wing absorption redward of Ly α (where there is no contamination from the Ly α forest). Our analysis implies that the EoR is not yet complete by $z = 7.1$, with the volume-weighted IGM neutral fraction constrained to $\bar{x}_{\text{H I}} = 0.40^{+0.21}_{-0.19}$ at 1σ ($\bar{x}_{\text{H I}} = 0.40^{+0.41}_{-0.32}$ at 2σ). This result is insensitive to the EoR morphology. Our detection of significant neutral H I in the IGM at $z = 7.1$ is consistent with the latest *Planck* 2016 measurements of the CMB Thompson scattering optical depth (Planck Collaboration XLVII).

Key words: cosmology: observations – cosmology: theory – dark ages, reionization, first stars – quasars: general – quasars: emission lines

1 INTRODUCTION

The epoch of reionisation (EoR) signals the end of the cosmic dark ages, when ionising radiation from the first stars and galaxies spreads throughout the Universe, beginning the last major baryonic phase change. This EoR is rich in astrophysical information, providing insights into the formation, properties and evolution of the first cosmic structures in the Universe.

Several recent $z \gtrsim 6$ observations have provided (controversial) information about the EoR (for a review, see e.g., Mesinger 2016). These come either from integral constraints on H II provided by the Thomson scattering of CMB photons (e.g. Planck Collaboration XIII 2015; George et al. 2015), or Ly α absorption by putative cosmic H I patches along the lines of sight towards $z \gtrsim 6$ objects. Since the cross-section at the Ly α line centre is large enough to saturate transmission even in the ionised intergalactic medium (IGM; requiring only trace values of neutral hydrogen: $x_{\text{H I}} \gtrsim$

$10^{-4} - 10^{-5}$), the latter constraints generally rely on the damping wing of the line. The relative flatness of the damping wing with frequency contributes a smooth absorption profile, which can result in optical depths of order a few during the EoR at frequencies around the redshifted Ly α line.

For galaxies, constraining damping wing absorption must be done with large samples, using their redshift evolution and/or clustering properties (e.g. Haiman & Spaans 1999; Ouchi et al. 2010; Stark et al. 2010; Pentericci 2011; Ono et al. 2012; Caruana et al. 2014; Schenker et al. 2014). QSOs however can be much brighter, allowing the detection of the EoR damping wing from a single spectrum. Most bright $z \gtrsim 6$ QSOs have a large region of detectable flux blueward of the rest frame 1216 Å, where the flux from the QSO itself is thought to facilitate transmission even for photons redshifting into the Ly α resonant core. If this so-called near zone is large, then the imprint of an EoR damping wing can be isolated as a smooth absorption component on top of the fluctuating resonant absorption (the Ly α forest) inside the near zone (e.g. Mesinger et al. 2004; Bolton & Haehnelt

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2007a,b; Schroeder et al. 2013). The intrinsic (unabsorbed) Ly α line profile can be reconstructed from the red side of the line (where absorption is minimal), assuming the line is symmetric (a reasonable assumption for bright QSOs; e.g. Kramer & Haiman 2009). However, one is faced with the challenge of modelling the statistics of the Ly α forest in the near zone, which depend on the ionising background and temperature.

The highest redshift QSO observed to date, the $z \sim 7.1$ object ULASJ1120+0641 (Mortlock et al. 2011, hereafter ULASJ1120), appears to have an uncharacteristically-small near zone: ~ 2 proper Mpc, roughly a factor of 3–4 smaller than generally found in $z \sim 6$ QSOs of comparable brightness (Carilli et al. 2010).¹ If the IGM is indeed undergoing reionisation at $z = 7.1$, cosmic H I patches along the line of sight could be close enough to the quasar to imprint a detectable damping wing signature away from the near zone edge, even redward of the Ly α emission line centre.² Redward of the Ly α line centre (and of any redshifted cosmological infall; e.g. Barkana & Loeb 2004), there is no contribution from resonant absorption in the Ly α forest. Not having to model the Ly α forest simplifies the analysis considerably. However, as it might contain a damping wing imprint, the red side of the observed emission line can no longer be used to independently reconstruct the Ly α line profile. Moreover, the intrinsic Ly α emission profile can vary significantly from object to object, complicating the usefulness of a composite emission template. Thus, *any analysis of the IGM damping wing would need to fold-in the significant uncertainties in the shape and amplitude of the intrinsic Ly α line profile.*

The difficulty in reconstructing the intrinsic emission of ULASJ1120 is further exacerbated by its peculiar emission line features. Mortlock et al. (2011) report an extremely large C IV blue-shift relative to its systemic redshift, which is larger than what has been observed in 99.9 per cent of all known QSOs. Bosman & Becker (2015) recently suggested that the observed Ly α emission of ULASJ1120 might be consistent with the subsample of objects with similar C IV properties, potentially alleviating the need for additional damping wing absorption.³ Correctly accounting for correlations

of line properties is therefore critical for any robust claims on reionisation from ULASJ1120.

In this work, we re-analyse the spectrum of ULASJ1120, improving on prior work with a combination of the following:

- We use the recently developed intrinsic Ly α emission line reconstruction method (Greig et al. 2016), which samples a covariance matrix of emission line properties from ~ 1500 moderate- z unobscured QSOs.
- We use the latest, large-scale (1.6 Gpc on a side), physics-rich simulations of the EoR (Mesinger et al. 2016) to extract 10^5 sightlines of opacity from $\sim 10^{12} M_\odot$ halos (typical of bright QSOs; e.g. Fan et al. 2006; Mortlock et al. 2011).
- We fold all uncertainties into a Bayesian framework, recovering robust constraints on the IGM neutral fraction at $z = 7.1$, which, for the first time, include rigorous statistical confidence intervals.

The remainder of this paper is organised as follows. In Section 2.1 we summarise the key components of the intrinsic Ly α reconstruction method, the observed spectrum of ULASJ1120 to be used in this analysis and the recovery of the reconstructed Ly α line profile. In Section 2.2 we discuss the semi-numerical reionisation simulations and the extraction of the synthetic damping wing profiles and in Section 2.3 we outline our combined analysis. In Section 3 we discuss the constraints on the IGM neutral fraction resulting from the imprint of the IGM damping wing, and in Section 4 we consider the possibility of a DLA contributing the damping wing imprint. Finally, in Section 5 we finish with our closing remarks. Throughout this work, we adopt the background cosmological parameters: $(\Omega_\Lambda, \Omega_M, \Omega_b, n, \sigma_8, H_0) = (0.69, 0.31, 0.048, 0.97, 0.81, 68 \text{ km s}^{-1} \text{ Mpc}^{-1})$, consistent with cosmic microwave background anisotropy measurements by the Planck satellite (Planck Collaboration XIII 2015) and unless otherwise stated, distances are quoted in comoving units.

2 METHOD

2.1 Reconstruction of the intrinsic Ly α profile

The analysis of the IGM damping wing imprint within the spectrum of ULASJ1120 hinges on the recovery of the intrinsic Ly α emission line profile. Already, in the previous section we have alluded to the difficulties in applying a QSO composite template to ULASJ1120. Within this work, we utilise the recently developed covariance matrix method of Greig et al. (2016) to obtain our reconstructed estimate of the intrinsic Ly α emission line profile.⁴

In this work, we make use of the Simcoe et al. (2012)

¹ Note that quantitative EoR constraints using just the apparent size of the near zone require assumptions about the QSO age, environment, and ionisation history (e.g. Mesinger et al. 2004; Maselli et al. 2007; Bolton et al. 2011).

² In principle, strong Ly α attenuation could also be caused by a damped Ly α absorber (DLA) intersected along the line of sight. However, such a system would have to have both an extremely high column density ($\log_{10}(N_{\text{H I}}/\text{cm}^{-2}) = 20.5 - 21$; Simcoe et al. 2012; Schroeder et al. 2013), and an extremely low metallicity ($Z \lesssim 10^{-4} Z_\odot$; e.g. Simcoe et al. 2012; Maio et al. 2013). As we discuss further below, the number density of such objects in a random IGM sightline is extremely small (e.g. Prochaska & Wolfe 2009).

³ Note that in their analysis, Bosman & Becker (2015) adopt the systemic redshift from the high-ionisation C III] line, rather than the subsequently improved determination from the atomic [C II] (Venemans et al. 2012). This impacts the relative velocity offsets of the emission lines, as well as the rest frame Ly α flux used in their analysis. Performing our analysis with the C III] redshift instead of the atomic [C II], we still find evidence of a damping wing, though with reduced significance.

⁴ An alternative approach could be to reconstruct a template using a principle component analysis (PCA) (e.g. Boroson & Green 1992; Francis et al. 1992; Suzuki et al. 2005; Suzuki 2006; Lee & Spergel 2011; Pâris et al. 2011; Simcoe et al. 2012). However, typically this is used for characterising the mean QSO composite obtained from fits to the full QSO spectrum with the fewest eigenvectors. How well this approach would work in reconstructing the intrinsic profile of Ly α , and characterising the properties of an individual source as peculiar as ULASJ1120, is beyond the scope of this work.

ULASJ1120 spectrum, obtained from the FIRE infrared spectrometer (Simcoe et al. 2008) on the Magellan/Baade telescope. This spectrum offers an order of magnitude improvement in spatial (frequency) resolution compared to the Mortlock et al. (2011) discovery spectrum, with a similar signal to noise.⁵ Throughout this work, we report all results in the QSO rest-frame, with which we convert from the observed frame using the atomic [C II] transition. The resulting ULASJ1120 redshift is $z = 7.0842 \pm 0.0004$ (Venemans et al. 2012)⁶.

2.1.1 Reconstruction procedure

Within this section we briefly summarise the major steps of the intrinsic Ly α profile reconstruction method of Greig et al. (2016), and refer the reader to that work for more in-depth discussions. Our approach is based on a covariance matrix characterising the emission line parameters. We first select a subsample of moderate- z ($2.08 < z < 2.5$), high signal to noise ($S/N > 15$) QSOs from SDSS-III (BOSS) DR12 (Dawson et al. 2013; Alam et al. 2015). Each QSO in our final sample of 1673 (using the ‘Good’ sample, which provides tighter constraints on the reconstruction profile) is then fit with a single power-law continuum, and a set of Gaussian profiles to characterise the emission lines and any possible absorption features contaminating the observed QSO spectrum. Each Gaussian profile is described by three parameters: a line width, peak height and velocity offset from the systemic redshift. For Ly α and C IV we allow for both a broad and narrow component Gaussian to describe the line profile, and single components for all other high and low-ionisation lines. After fitting all QSOs, and performing a visual quality assessment to refine our QSO sample, we construct our covariance matrix from the four most prominent high ionisation lines, Ly α , C IV, Si IV + O IV] and C III].

With the covariance matrix in hand, we can reconstruct the intrinsic Ly α line profile of ULASJ1120 as follows:

- Using the fitting procedure described above, we fit the spectrum of ULASJ1120 far redward of the extent of the Ly α line profile. We chose $\lambda > 1275\text{\AA}$ as the blue edge for the fit somewhat arbitrarily, but verify that this choice does not have an impact on the results.
- From this fit (shown in Figure 1), we obtain estimates of ULASJ1120’s continuum and of its Si IV + O IV], C IV and C III] line profiles.
- Using these estimates, we collapse the 18-dimensional (Gaussian distributed) covariance matrix into a six dimensional estimate of the intrinsic Ly α emission line profile (two component Gaussian each with an amplitude, width and velocity offset).

⁵ In order to test the robustness of our fit to ULASJ1120, we additionally performed our MCMC fitting approach on the Mortlock et al. (2011) discovery spectrum. While this spectrum has an order of magnitude lower resolution, this should not impact the recovery of the strong high-ionisation lines. Not shown here, we confirm that indeed we do recover similar fits for all emission line features.

⁶ The uncertainty on the redshift determination is implicitly accounted for within our MCMC fitting approach, by allowing the velocity offset of each individual emission line to be a free parameter.

- We apply a prior within the range $1230 < \lambda < 1275\text{\AA}$. This is performed by simultaneously fitting the Ly α + N V (1240.81 \AA) and Si II (1262.59 \AA) lines (where we sample the Ly α profile from the six dimensional distribution), using the observed noise from the FIRE spectrum to obtain a χ^2 likelihood for the reconstructed profile. In other words, we require our profiles to fit the observed spectrum over the range $1230 < \lambda < 1275\text{\AA}$. This final step notably reduces the errors on the reconstructed Ly α profile (shown in Figure 2), ruling out extreme profiles which are inconsistent with the actual observed spectrum. We note that the wavelength range by construction has to be redward of any significant damping wing absorption; however the actual range is again somewhat arbitrary, and we verify that our results are not sensitive to this choice.

2.1.2 Reconstruction of ULASJ1120+0641

In Figure 1, we present the MCMC template fitting of ULASJ1120 at $\lambda > 1275\text{\AA}$. In the top panel, the red-dashed curve corresponds to the best-fit QSO continuum, whereas in the remaining zoomed-in panels we present the best-fits to the various emission line profiles, using either a single or double component Gaussian as described above. Compared to the QSO spectra used in the construction of the covariance matrix in Greig et al. (2016), the FIRE spectrum is considerably noisier.

Immediately obvious from Figure 1 is the significant blueshift observed amongst all the high-ionisation lines. In addition to the already reported strong blueshift of C IV Mortlock et al. (2011), we note that the N V (not fit), Si IV + O IV] and C III] lines appear to be equally strongly blue shifted. At the same time, the low ionisation lines, O I and C II do not appear to be blue shifted at all. Furthermore, while not shown in Figure 1 or observed in the Simcoe et al. (2012) FIRE spectrum, the Mg II line also does not have a significant blue shift (Mortlock et al. 2011). This behaviour is well known, which highlights that the physics governing the low and high ionisation lines stem from different processes or physical regions. We stress that this strong observed blueshift in all high-ionisation lines is automatically accounted for by the covariance matrix reconstruction pipeline.

Note that, in the FIRE spectrum, the Si IV + O IV] line is strongly affected by both night sky OH lines and telluric absorption bands. While attempts were made to correct this in the spectrum, they will still leave an imprint in the form of lower signal to noise and larger residuals. Within this work we attempt to mask out the worst of these lines, however we caution that the Si IV + O IV] line may still be contaminated. However, we note that the Si IV + O IV] emission line is the least important of the three high-ionisation lines used to reconstruct the intrinsic Ly α line profile. Therefore, while the characterisation of the Si IV + O IV] line profile is likely to be contaminated, the uncertainties arising from this will not greatly impact our reconstructed Ly α line profile.

In Figure 2, we show the reconstructed intrinsic Ly α emission line profile. The red curve is the best-fit profile obtained by jointly sampling the Ly α line profile and the wavelength range $1230 < \lambda < 1275\text{\AA}$, while the black curve is the observed spectrum sampled in 0.2\AA bins. Given that our reconstruction procedure returns a six-dimensional like-

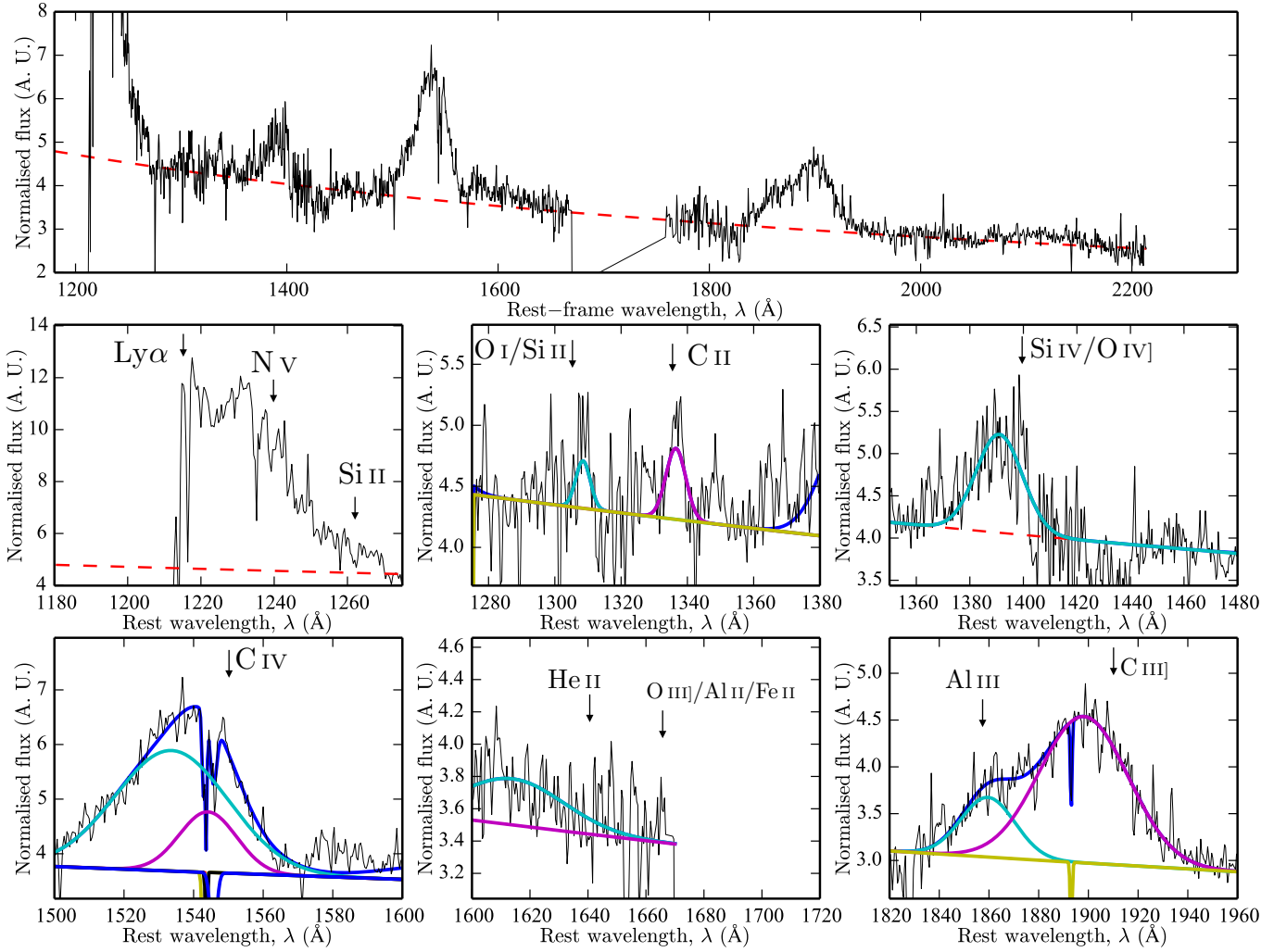


Figure 1. A zoom-in highlighting the MCMC QSO fitting procedure of Greig et al. (2016) applied to the rest-frame FIRE spectrum (Simcoe et al. 2012). This method includes the identification of ‘absorption’ features (e.g. the bottom left and bottom right panels), which improves our ability to recover the emission line profiles. The flux is normalized to unity at 1450 Å rest-frame (1 A. U. = 10^{-17} erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$). Arrows denote the systemic redshift of each line, obtained from the recovered atomic [C II] redshift (Venemans et al. 2012). *Top:* A single power-law continuum component fit to the QSO spectrum (red dashed curve). *Middle left:* The obscured Ly α peak profile (not-fit). *Middle centre:* Two low-ionisation lines, O I/Si II] (cyan) and C II (magenta). *Middle right:* Single component Gaussian fit to the Si IV + O IV] blended line complex. *Bottom left:* Two-component fit to C IV. *Bottom centre:* Low ionisation lines, He II (cyan; no prevalent emission, therefore the line profile is unconstrained) and O III] (within the excised region, therefore not fit). *Bottom right:* Single component fit to C III] (magenta) and single Gaussian Al III component (cyan).

likelihood function, in order to characterise the scale of the 68 per cent uncertainties on the reconstructed Ly α profile we randomly sample this likelihood function to extract representative profiles. In Figure 2 we present 300 reconstructed Ly α line profiles denoted by the thin grey lines which are within the 68 per cent uncertainties. These profiles highlight the relative scale of the variations in the total Ly α line profile peak height, width and location. Note, our analysis pipeline operates directly on a large number of these sampled profiles, and not just the maximum-likelihood reconstructed profile (red curve).

Qualitatively, the reconstructed Ly α line profile is similar to the composite QSO spectrum presented in Mortlock et al. (2011) and in Simcoe et al. (2012), albeit with a slightly higher amplitude at the Ly α line centre. A notable advantage of our approach is the statistical characterisation of

the Ly α line offset, using the covariance matrix. As shown in Bosman & Becker (2015), the location of the Ly α line centre of the reconstructed profile is crucial for the analysis of the IGM damping wing. Unfortunately, the blue shifts observed in ULASJ1120 exceed those found in all of the 1673 QSOs from which we construct the covariance matrix. The mean blue shift of the C IV ionisation line profile of ULASJ1120 (obtained from combining the narrow and broad components), $\Delta v \sim 2500$ km/s, is a $\sim 4\sigma$ outlier from our QSO sample. Thus in the reconstruction procedure for ULASJ1120, we have to extrapolate the Gaussian covariances.

We test this extrapolation by additionally performing the Ly α profile reconstruction using an artificial blue-shift correction. Following Bosman & Becker (2015), we take the systemic redshift from the C III] line (instead of our fiducial

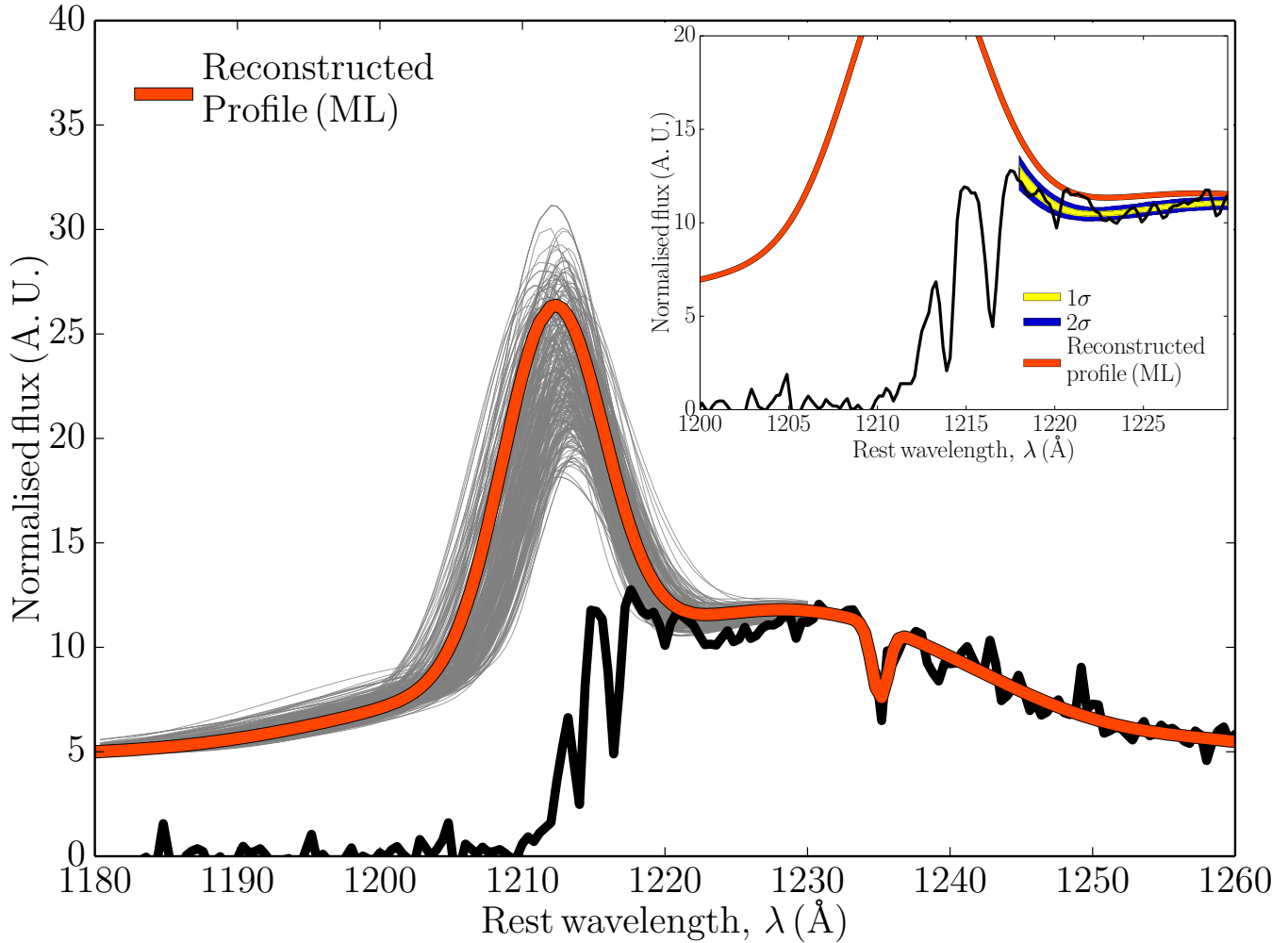


Figure 2. The reconstructed maximum likelihood $\text{Ly}\alpha$ emission line profile (red curve) recovered from our covariance matrix method including an additional prior on the flux amplitude within the wavelength range $1230 < \lambda < 1275\text{\AA}$. The thin grey curves denote 300 $\text{Ly}\alpha$ line profiles extracted from the reconstructed six-dimensional $\text{Ly}\alpha$ likelihood function. These curves are selected to be within 68 per cent of the maximum likelihood profile, and highlight the relative scale of the errors on the reconstructed $\text{Ly}\alpha$ line profile. The black curve denotes the observed spectrum of ULASJ1120. *Inset:* A zoom-in around $\text{Ly}\alpha$ highlighting the recovered imprint of the IGM damping wing profile (Section 2.3). The yellow (blue) shaded region denotes the 1σ (2σ) span of total (intrinsic + damping wing absorption) flux over the fitted region. For reference, the red curve is the maximum likelihood intrinsic profile (same as main figure). The stretch between $1222 - 1227\text{\AA}$ is especially difficult to match without the aid of the IGM damping wing from an incomplete reionisation.

atomic C II). As noted in Section 2.1.2, the C III] emission line appears equally strongly blue shifted as C IV and the other high ionisation lines; therefore, by using the C III] redshift we can artificially remove the strong C IV velocity offset. After performing the $\text{Ly}\alpha$ reconstruction pipeline on this artificially corrected spectrum, we recover a quantitatively similar $\text{Ly}\alpha$ line profile shape, well within our $1-\sigma$ uncertainties. Note that our pipeline and the resulting uncertainties automatically account for all of the line correlations pointed out by Bosman & Becker (2015).

2.2 The IGM damping wing during the EoR

As stated above, the observed spectrum redward of the $\text{Ly}\alpha$ line centre depends on the intrinsic emission (discussed in the previous section), and the damping wing absorption from (putative) cosmic H I patches along the line of sight (LoS). To statistically characterise the latter, we make

use of the publicly-available Evolution of 21-cm Structure (EOS; Mesinger et al. 2016)⁷ 2016 data release. These semi-numerical reionisation simulations are 1.6 Gpc on a side with a 1024^3 grid, and include state-of-the-art sub-grid prescriptions for inhomogeneous recombinations and photo-heating suppression of star-formation. The 2016 EOS data release corresponds to two simulation runs, with the efficiency of supernovae feedback adjusted to approximately bracket the expected EoR contribution from faint galaxies. The two runs are:

- **Faint galaxies** – the EoR is driven by galaxies residing in haloes with masses of $10^8 \lesssim M_h/M_\odot \lesssim 10^9$, and is characterised by numerous small cosmic H II regions. Hereafter we will refer to the EoR morphologies resulting from this simulation as **Small H II**.

⁷ <http://homepage.sns.it/mesinger/EOS.html>

- **Bright galaxies** – the EoR is instead driven by galaxies residing in haloes with masses of $M_h \sim 10^{10} M_\odot$, and is characterised by spatially more extended H II structures. We refer to these simulated EoR morphologies as **Large H II**.

We note that the LARGE H II ionisation fields have a factor of \sim few–10 times more power on large scales during the EoR, compared to the SMALL H II ionisation fields. Although these are two opposite extremes in terms of H II region sizes, the SMALL H II EoR morphology is likely more realistic (see the discussion in Mesinger et al. 2016), and so we use this simulation as our fiducial model. Nevertheless, we include both extremes to explore the dependence of our results on EoR morphology.

We construct samples of sightlines through our simulations which are terminated on one end at a halo, and then extended in a random direction through the simulation volume for a distance of 200 comoving Mpc. Along each sightline, we sum the contributions from all encountered H I patches to construct a composite optical depth for the damping wing (e.g. Miralda-Escudé 1998). We purposefully exclude the H I contribution from pixels ≤ 16 comoving Mpc (2 physical Mpc) from the QSO host halo. This corresponds to the minimum possible radius of the H II region around ULASJ1120 inferred from measurements of its near zone (Mortlock et al. 2011). We do not explicitly include the flux from the QSO in our reionisation maps. Doing so would require assumptions about the QSO lifetime and ionising luminosity. Neglecting the QSO ionising contribution implies that the surrounding H II region could be larger than predicted by our EoR models. For a given \bar{x}_{HI} a larger surrounding H II region implies a smaller integrated damping wing optical depth. Thus if the QSO contributes in growing the surrounding H II region, our modelled optical depths should be associated with even higher values of \bar{x}_{HI} , shifting the PDFs we present below towards larger \bar{x}_{HI} .

At $z = 7.1$, we select 10^4 identified haloes in the mass range $6 \times 10^{11} < M_h/M_\odot < 3 \times 10^{12}$, consistent with the inferred dynamical mass of the host halo of ULASJ1120 (Venemans et al. 2012). Importantly, these higher host halo masses, made possible by the large-scale EOS simulations, are a notable improvement over previous studies (e.g. Bolton et al. 2011) as they better capture the bias and scatter of the QSOs locations inside reionisation fields. Though the lines of sight begin 16 Mpc from the host haloes, this bias and scatter may still be important (see e.g. fig. 2 of Mesinger & Furlanetto 2008 and fig. 3 of Mesinger 2010). We use 10 LoSs per host halo, resulting in a total sample of 10^5 synthetic IGM damping wing profiles for each sampled \bar{x}_{HI} and EoR morphology (SMALL H II and LARGE H II). Since we wish to leave the IGM neutral fraction at $z = 7.1$ as a free parameter, we follow the common practice of sampling ionisation fields at various redshifts corresponding to a given \bar{x}_{HI} (e.g. McQuinn et al. 2007; Sobacchi & Mesinger 2015).

2.3 Joint fitting of the intrinsic emission and IGM damping wing

Having outlined the reconstruction of the intrinsic Ly α line profile of ULASJ1120 in Section 2.1 and the IGM damping wing profiles in Section 2.2 we now combine them to simul-

taneously fit the observed spectrum. Our fitting procedure consists of the following steps:

(i) The intrinsic Ly α line profile recovered in Section 2.1.2 is fully described by a six dimensional likelihood function (three parameters for each of the two Gaussian components), characterising the uncertainties and correlations amongst the Ly α line profile parameters, constrained by the spectrum at $\lambda > 1230 \text{ \AA}$. We draw $\sim 10^5$ Ly α line profiles directly from this six dimensional likelihood.

(ii) Each line profile is then multiplied by each of the 10^5 EoR damping wing absorption profiles, resulting in a total sample of $\sim 10^5 \times 10^5$ mock spectra for each value of \bar{x}_{HI} .

(iii) Each mock spectrum is then compared with the observed spectrum of ULASJ1120 in the wavelength range $1218 \text{ \AA} < \lambda < 1230 \text{ \AA}$ ⁸. The quality of the fit is characterized by a (χ^2 based) likelihood, using the observational errors of the spectrum.

(iv) The resulting likelihood, averaged over all $\sim 10^{10}$ mock spectra, is then assigned to that particular \bar{x}_{HI} .

(v) Steps (ii)–(iv) are repeated for each trial value of \bar{x}_{HI} . We sample the range $0.01 \leq \bar{x}_{\text{HI}} \leq 0.95$, with 40 (28) individual snapshots for the SMALL H II (LARGE H II) simulations (note that the EoR proceeds more rapidly in the LARGE H II model, resulting in a coarser \bar{x}_{HI} sampling for outputs at fixed redshift intervals).

(vi) We normalise the resulting relative likelihoods, ending with a final 1D probability distribution function (PDF) of \bar{x}_{HI} for each of the EoR morphologies.

The above steps effectively result in the construction a 3D likelihood which is a function of: (i) \bar{x}_{HI} ; (ii) the EoR damping wing sightline; and (iii) the intrinsic emission profile. Our final constraints on \bar{x}_{HI} are obtained by marginalising over (ii) and (iii).

3 RESULTS

In the inset of Figure 2, we present the confidence intervals on the product of the reconstructed Ly α line profile and the synthetic IGM damping wing profiles within the fitting interval $1218 \text{ \AA} < \lambda < 1230 \text{ \AA}$. For reference, the red curve is the intrinsic Ly α emission line profile with the maximum likelihood from our reconstruction procedure. The impact of the damping wing contribution is highlighted by the offset of the shaded regions and the red curve. In the main panel of Figure 2, we present a small subset (300) of recovered Ly α line profiles to convey the relative uncertainties in the reconstruction pipeline. Note that the wavelength stretch between $1222 - 1227 \text{ \AA}$ is especially difficult to fit purely with the intrinsic profiles alone. As we shall see below, we

⁸ The choice of 1230 \AA is motivated by the blue edge of the prior discussed in Section 2.1.2, while the choice of 1218 \AA is motivated by ensuring that we are sufficiently far from the influence of any infalling or local gas (e.g. Barkana & Loeb 2004), which is not modelled by our EoR simulations. Note that the circular velocity of the host halo (e.g. Venemans et al. 2012) corresponds to a rest frame offset of $\sim 2 \text{ \AA}$. We verify that changing this range only impacts our \bar{x}_{HI} constraints at the percent level by considering the following alternatives: $1220 \text{ \AA} < \lambda < 1230 \text{ \AA}$, $1220 \text{ \AA} < \lambda < 1228 \text{ \AA}$ and $1218 \text{ \AA} < \lambda < 1228 \text{ \AA}$.

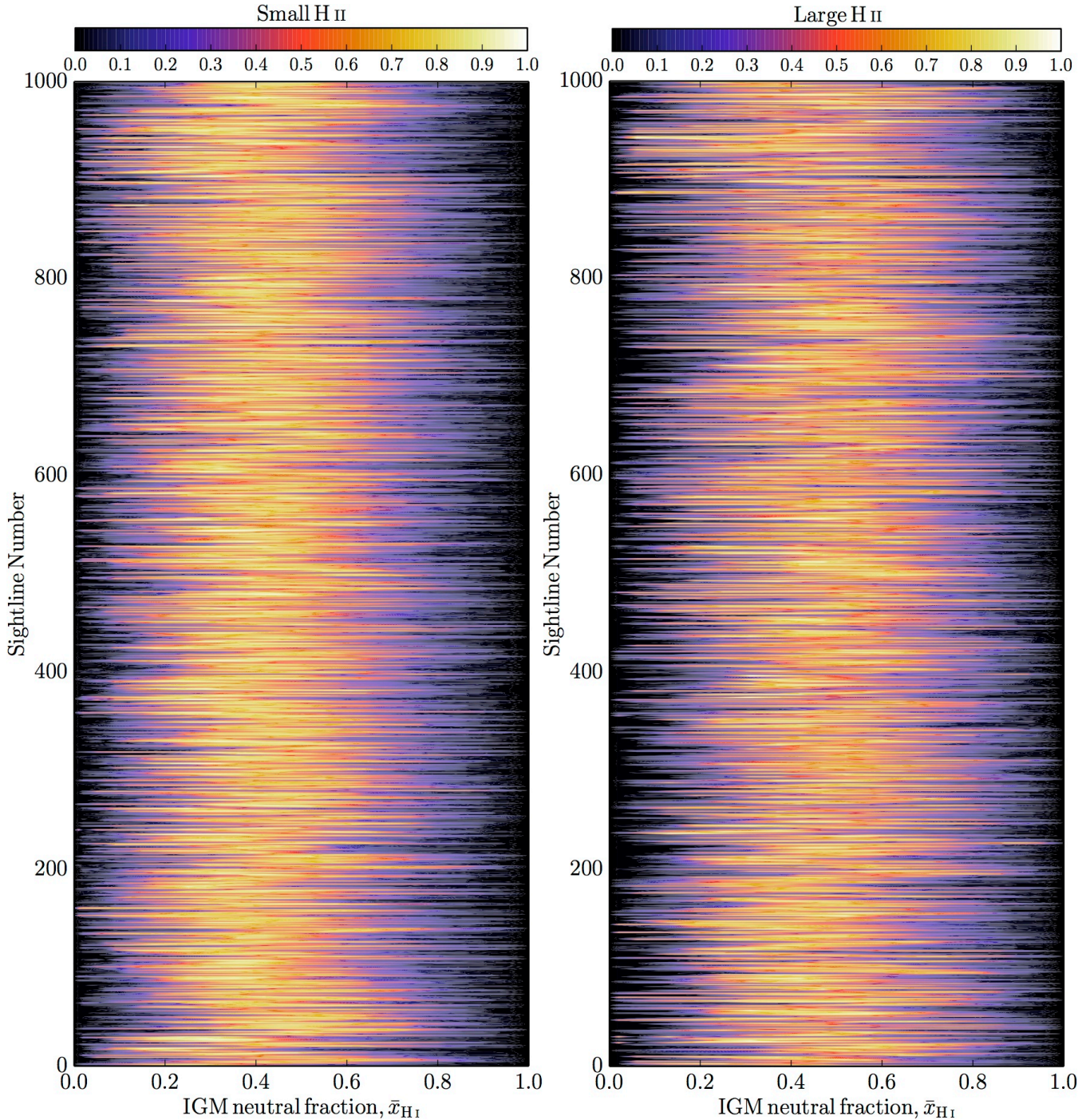


Figure 3. 1D PDFs of the IGM neutral fraction drawn from a subsample of 1000 lines of sight for each of the two EoR simulations used in our analysis (Mesinger et al. 2016). Colour bars denote the amplitude of the PDFs, $P(\bar{x}_{\text{HI}})$. Note that the peaks of the PDFs of each sightline are normalised to unity purely to aid the visualisation. The shifting locations of the peaks per sightline are indicative of the sightline-to-sightline variation. In the left panel, the individual sightline PDFs correspond to the SMALL H II EoR simulations (reionisation driven by faint galaxies producing small cosmic H II regions) whereas the right panel corresponds to the LARGE H II EoR simulations (reionisation driven by bright galaxies producing large cosmic H II regions). Averaging over the full sample of 10^5 sightlines (i.e. collapsing along the vertical direction) results in the 1D PDFs of \bar{x}_{HI} shown in the following figure.

require a non-zero IGM damping wing contribution to fit the observed spectrum of ULASJ1120.

Before presenting our final constraints on \bar{x}_{HI} , we showcase the EoR sightline-to-sightline scatter in Figure 3. For each of a randomly selected subsample of 1000 sightlines shown in the figure, we average over the full distribution of

the reconstructed Ly α intrinsic profiles, in order to generate a \bar{x}_{HI} PDF for that sightline. Collapsing (marginalising) over the vertical direction (sightline number) for the entire sample of 10^5 LoSs recovers the full 1D marginalised PDF (step (vi) of Section 2.3; see Figure 4). Sightlines extracted

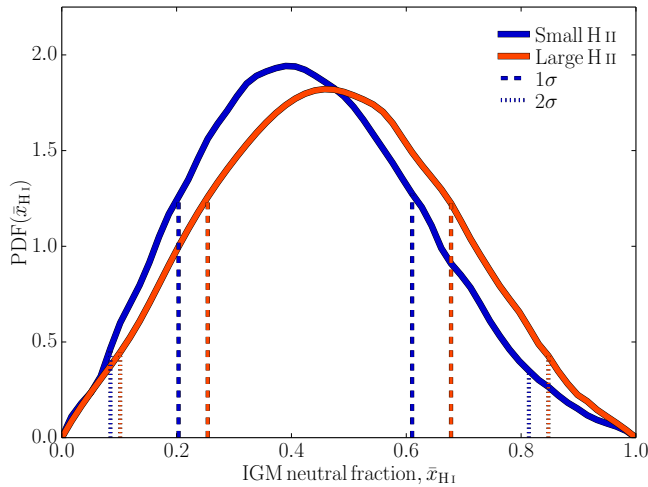


Figure 4. PDFs of the $z = 7.1$ IGM neutral fraction obtained by marginalising over all synthetic IGM damping wing absorption profiles and reconstructed intrinsic Ly α emission line profiles. The red curve corresponds to the LARGE H II simulations (right panel of Figure 3) whereas the blue curve corresponds to the SMALL H II simulation (left panel of Figure 3). Dashed (dotted) curves correspond to the 1 (2σ) constraints on \bar{x}_{HI} for the respective morphologies. Both simulations recover consistent results, favouring a strong damping wing imprint from a significantly neutral IGM ($\bar{x}_{\text{HI}} \sim 0.4$).

from the SMALL H II and LARGE H II simulations appear on the left and right, respectively.

On average, we recover a similar range for the preferred IGM neutral fraction for both EoR morphologies. However, there is significant sightline-to-sightline variation, shifting the peaks of the \bar{x}_{HI} distributions by tens of per cent. This highlights the importance of sampling a large number of IGM damping wing profiles. Our full sample consists of 10^5 sightlines through inhomogeneous reionisation, compared with 100 sightlines through homogeneous reionisation in the preliminary studies of Bolton et al. (2011) and Keating et al. (2015).

Finally, in Figure 4 we present the main result of this work: 1D PDFs of \bar{x}_{HI} . These are obtained by marginalising over all combinations of reconstructed intrinsic Ly α line profiles and synthetic IGM damping wing sightlines for a given \bar{x}_{HI} . The blue curve corresponds to the SMALL H II EoR morphology, while the red curve corresponds to the LARGE H II EoR morphology. Dotted (dashed) curves correspond to the 1 (2σ) constraints on \bar{x}_{HI} for the respective morphologies:

- **Small H II;** $\bar{x}_{\text{HI}} = 0.40^{+0.21}_{-0.19}$ (1σ) and $0.40^{+0.41}_{-0.32}$ (2σ)
- **Large H II;** $\bar{x}_{\text{HI}} = 0.46^{+0.21}_{-0.21}$ (1σ) and $0.46^{+0.39}_{-0.37}$ (2σ).

As mentioned earlier (and discussed in Mesinger et al. 2016), the SMALL H II model is likely more accurate and we adopt it as our fiducial constraint. We note that the constraints on \bar{x}_{HI} are very similar for both SMALL H II and LARGE H II. This indicates that the damping wing imprint is not very sensitive to how the cosmic neutral patches are distributed at a fixed value of \bar{x}_{HI} .

4 COULD THE DAMPING WING COME FROM A DAMPED LYMAN ALPHA SYSTEM?

In this work we found evidence of a damping wing imprint on the red side of the Ly α line of ULASJ1120, and quantified the corresponding constraints on the IGM neutral fraction. However, a damping wing could instead be produced by an intervening damped Ly α system, at least in principle. Indeed most high- z gamma-ray bursts (GRBs) show evidence of a DLA in their spectra (e.g. Chornock et al. 2013, 2014; Totani et al. 2014). However, the GRB DLAs are associated with the GRB host galaxy, while a DLA in the spectra of ULASJ1120 would have to be at least 16 Mpc away from the QSO host galaxy. As has been pointed out previously, finding such an object in a random skewer through the IGM is highly unlikely. To mimic our results, the required column density of the DLA would have to be $\log_{10}(N_{\text{HI}}/\text{cm}^{-2}) > 20 - 21$ (see also Simcoe et al. 2012; Schroeder et al. 2013). Such systems are extremely rare. Following Schroeder et al. (2013), we note that an extrapolation of the incidence rate of DLAs (Prochaska & Wolfe 2009; Songaila & Cowie 2010) to $z \sim 7$ implies an abundance of $\lesssim 0.05$ DLAs per unit redshift with comparable column densities (see fig. 8 in Songaila & Cowie 2010). Thus only $\lesssim 0.3$ per cent of IGM segments with a length corresponding to the ULASJ1120 near zone size ($\Delta z_{\text{NZ}} \sim 0.05$) would contain a DLA. We also note that Bolton et al. (2011) found only $\sim 5\%$ of their mock sightlines contained a DLA, even using a self-shielding prescription which notably overestimates their abundances (Rahmati et al. 2013; Keating et al. 2014; Mesinger et al. 2015). Thus, the a-priori presence of a DLA can approximately be excluded at $\gtrsim 2-3\sigma$ on the basis of the required column density alone.

Even more damning is the fact that there is no evidence of associated metal line absorption in ULASJ1120. Therefore a putative DLA would have to be atypically pristine, with a metallicity of $Z \lesssim 10^{-4} Z_{\odot}$ which is inconsistent with every other DLA observation (e.g. Simcoe et al. 2012; Cooke et al. 2015). We therefore conclude that the damping wing absorption seen in ULASJ1120 is highly unlikely to originate from a DLA.

5 CONCLUSION

In this work, we obtain constraints on the $z = 7.1$ IGM neutral fraction by isolating its damping wing absorption in the spectrum of QSO ULASJ1120. We use a state-of-the-art Bayesian framework which for the first time is able to jointly sample both: (i) the uncertainty in the QSO intrinsic emission; and (ii) the EoR sightline-to-sightline variation. For (i), we use a covariance matrix of emission line properties (Greig et al. 2016) to reconstruct the intrinsic Ly α line profile. For (ii), we use the latest, large-scale simulations of patchy reionisation (Mesinger et al. 2016). After marginalising over (i) and (ii), we obtain robust constraints on the IGM neutral fraction. For our fiducial reionisation model, these are: $\bar{x}_{\text{HI}} = 0.40^{+0.21}_{-0.19}$ (1σ) and $0.40^{+0.41}_{-0.32}$ (2σ). We note that the constraints are very insensitive to the EoR model, at a fixed global neutral fraction (see Figure 4).

Our results correspond to the first measurement of the

ionisation state of the IGM at $z \sim 7$, with a well-defined confidence range (as opposed to upper/lower limits). They are consistent with the latest *Planck* measurements of the Thompson scattering optical depth, which independently appeared as this work was nearing completion (Planck Collaboration XLVII 2016).

The framework we developed can easily be applied to future QSO observations. Moreover, the analysis can be extended to incorporate the transmission statistics in the QSO near zone (blueward of $\text{Ly}\alpha$). This would introduce additional uncertainties, but would allow the analysis to be extended to other bright $z \sim 6\text{--}7$ QSOs which have a much larger near zone, and thus a correspondingly weaker damping wing imprint on the red side of the line (Schroeder et al. 2013). We defer this to future work.

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